AFRL-PR-WP-TM-2006-2003

FLUID MECHANICS OF COMPRESSION SYSTEM FLOW CONTROL

David Car
Steven L. Puterbaugh

Fan/Compressor Branch (AFRL/PRTF)
Turbine Engine Division
Propulsion Directorate
Air Force Research Laboratory, Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7251

JULY 2005

Interim Report for 07 April 2005 – 07 May 2005

Approved for public release; distribution is unlimited.

STINFO INTERIM REPORT

PROPULSION DIRECTORATE
AIR FORCE MATERIEL COMMAND
AIR FORCE RESEARCH LABORATORY
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7251

NOTICE

PAO Case Number: AFRL/WS-05-1691
Date cleared: 18 Jul 2005

THIS TECHNICAL REPORT IS APPROVED FOR PUBLICATION.

//S//

STEVEN L. PUTERBAUGH, Ph.D.
Project Monitor
Fan/Compressor Branch

//S//

JOHN E. LUEKE
Chief
Fan/Compressor Branch

//S//

WILLIAM W. COPENHAVER, Ph.D.
Principal Scientist
Turbine Engine Division

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*
July 2005

2. REPORT TYPE
Interim

3. DATES COVERED *(From - To)*
04/07/2005 – 05/07/2005

4. TITLE AND SUBTITLE
FLUID MECHANICS OF COMPRESSION SYSTEM FLOW CONTROL

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
David Car
Steven L. Puterbaugh

5d. PROJECT NUMBER
2307

5e. TASK NUMBER
S1

5f. WORK UNIT NUMBER
28

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Fan/Compressor Branch (AFRL/PRTF)
Turbine Engine Division
Propulsion Directorate
Air Force Research Laboratory, Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7251

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-PR-WP-TM-2006-2003

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Propulsion Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson AFB, OH 45433-7251

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/PRTF

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-PR-WP-TM-2006-2003

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Report contains color.

Prepared for AFOSR Annual Program Review.

14. ABSTRACT

The aim of Fluid Mechanics of Compression System Flow Control is to increase the diffusion capacity of an axial compressor stator through the application of bladesurface-mounted flow control. The experimental portion of the work employs a small wind tunnel that allows the investigation of flow control concepts applied to a simulated single stator passage. Baseline results are presented along with those of three flow control modules; all are variations of blowing (no aspiration) flow control using a planar jet behind a backward facing step positioned upstream of the passage curvature. Two preliminary investigations are presented. The first includes the effect of the thickness of the lip separating the main stream from the core stream of the backward facing step and its impact on the flow control effectiveness. The second introduces streamwise vorticity via flat plate vortex generators as a means of enhancing the interaction between the blowing jet and the core stream.

15. SUBJECT TERMS

flow control, turbomachinery, vortex generator

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			
Unclassified	Unclassified	Unclassified	SAR	12	Steven L. Puterbaugh **19b. TELEPHONE NUMBER** *(Include Area Code)* (937) 255-7432

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

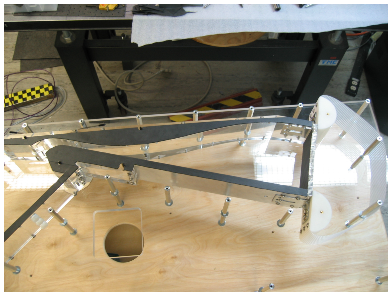
FLUID MECHANICS OF COMPRESSION SYSTEM FLOW CONTROL

David Car
Steven Puterbaugh
Propulsion Directorate
Wright-Patterson AFB, Ohio

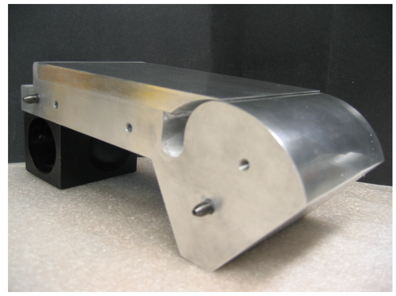
Abstract
The aim of *Fluid Mechanics of Compression System Flow Control* is to increase the diffusion capacity of an axial compressor stator through the application of blade-surface-mounted flow control. The experimental portion of the work employs a small wind tunnel that allows the investigation of flow control concepts applied to a simulated single stator passage. Baseline results are presented along with those of three flow control modules; all are variations of blowing (no aspiration) flow control using a planar jet behind a backward facing step positioned upstream of the passage curvature. Two preliminary investigations are presented. The first includes the effect of the thickness of the lip separating the main stream from the core stream of the backward facing step and its impact on the flow control effectiveness. The second introduces streamwise vorticity via flat plate vortex generators as a means of enhancing the interaction between the blowing jet and the core stream.

Introduction
Flow control particular to axial compression systems has become a very active research topic for the last few decades.[1–4] It has the potential to open the design envelope for axial compressors to higher loading levels. This translates into higher overall pressure ratios for reduced thrust specific fuel consumption (TSFC). Increased loading levels also increases thrust-to-weight(T/W) ratios by reducing turbine engine axial length for a given pressure ratio. The Air Force Versatile Affordable Advanced Turbine Engine (VAATE) program cycle requirements will drive a much higher overall pressure ratio, thus requiring larger pressure rise per stage in order to keep overall engine length reasonable.

The research objective of this work is to increase the diffusion capability of a stator flow passage via flow control methods. To assist in this effort, an experimental flow control research rig has been designed and will be briefly outlined in this report. Following will be the initial investigation and comparison of three flow control modules; all are variations on a theme of blowing only flow control using a planar jet behind a backward facing step. Two of the variations are preliminary investigations into the effect of the separation distance between the primary and secondary streams due to finite material thickness separating the streams. The third variation seeks to embed streamwise vorticity via vortex generators into the shear layer between the primary and secondary flow streams. The goal is to enhance the interaction between



(a) Top View of FCAD wind tunnel



(b) Flow control module with slot

Figure 1: FCAD Wind Tunnel

the streams and thereby reduce the secondary flow requirements for a given level of diffusion.

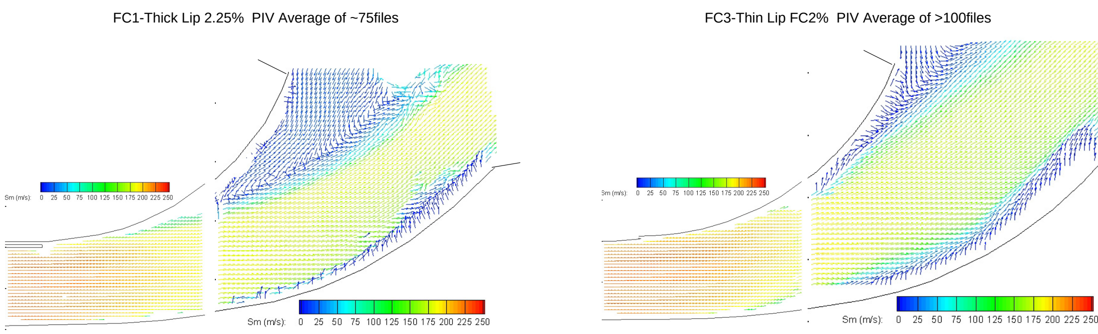
Experimental Apparatus

The Flow Control Augmented Diffusion (FCAD) wind tunnel is an atmospheric in-draft design. After passing through a bellmouth and flow straightener, the airflow accelerates through a converging inlet of roughly 12:1 area contraction to a rectangular throat, 1.5 x 10.2 cm (0.6 x 4.0 in). The throat, typically operated at Mach 0.7, is the beginning of the curved diffusor test section. The diffusor geometry is based on aggressive goals for an axial compression system. The diffusor passage has an exit-to-throat area ratio of 2.92, a flow turning angle of 70 degrees, with suction (convex) side radius of curvature nearly constant at 5.1 cm (2.0 in). Following the diffusor is a sudden expansion into a rectangular settling chamber. An adaptor piece guides the flow from the settling chamber into a flexible 7.6 cm (3 in) diameter duct connected to the primary flow driver. Figure 1 illustrates the basic flowpath from the inlet (at right) to the dump chamber (left).

Because present research goals include identification of key physical mechanisms relating diffusion and flow control, the tunnel was designed with optical access as a priority. The top and bottom walls are transparent acrylic sheets, and sandwiched in between are wall segments with height of 10.2 cm (4 in). Defining the suction (convex) side of the curved diffusor test section is a readily replaceable aluminum module for testing various flow control concepts. One such module is shown in Figure 1. The planar jet height for these studies was fixed at 0.508 mm and the jet surface was constructed as follows: 1) The baseline convex surface was a constant radius of 50.8 mm ; 2) This radius was reduced 1.397 mm at the throat to accomodate the jet and lip thickness; 3) A linear function in the angular coordinate was used to fit this radius to the 50.8 mm radius at the exit of the passage.

Lip Thickness Study

The influence of the separation distance between the core flow and jet flow due to the finite material thickness of the upper plate on the flow field was investigated. Two material thickness were tested: 0.635 mm and 0.127 mm which are 125% and 25% of the planar jet size respectively. The 0.127 mm thickness was achieved by honing the upper surface of the 0.635 mm plate at a 5 degree angle. Figure 2 shows the post processed DPIV average flowfield for a flow fraction of approximately 2% for both the 125% and 25% cases. The 25% lip thickness shows much more diffusion over the 125% case.



(a) Composite image of 125% primary to secondary separation distance and 2.25% flow control

(b) Composite image of 25% primary to secondary separation distance and 2.00% flow control

Figure 2: Effect of Core and Jet Separation on Diffusion Effectiveness

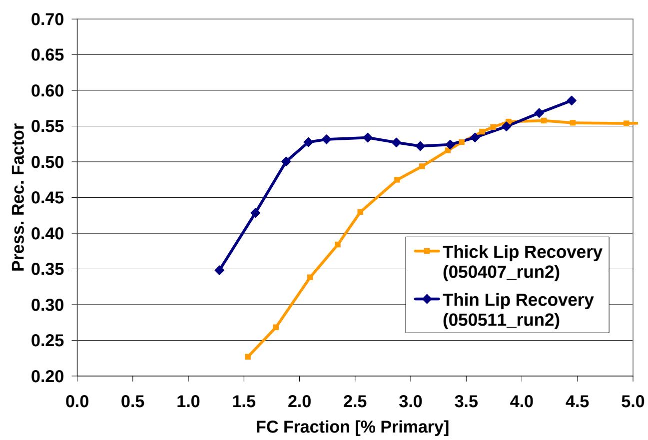


Figure 3: Effect of Core and Jet Separation on Static Pressure Recovery

As is clear from Figure 2, larger regions of flow separation exist for the 125% thickness case. Consequently, the 25% lip thickness requires half the secondary flow requirement for the same static pressure rise coefficient versus the 125% case as seen in Figure 3. This has significant implications regarding the manufacturing requirements for such an approach.

Streamwise Vorticity Addition
It is postulated that increased streamwise vorticity will enhance the mixing between the main and secondary streams resulting in a persistent momentum exchange that will signficantly delay separation. In order to effect this condition, pairs of counter-rotating streamwise vortices are introduced via flat plate vortex generators placed on the upper surface of the flow control module plate as shown in Figure 4. Vortex pairs were created such that their induced motion was toward the surface and the planar jet.[5,6]

The desired circulation strength, Γ, and spacing, d, for the vortex pair was determined by taking a much simplified approach to the flowfield. The flowfield was approximated as undergoing a transition from velocity V_1 at the throat to V_2 at the exit in a linear fashion. A relationship between streamwise position and time could then be obtained. An approximation of the circulation generated by a NACA 0012 vortex generator[7] was used to relate the VG geometry to circulation strength. It was also assumed that the streamwise vortex pair advects with the background flow field. Due to space limitations, the final result will only be presented here. A functional relationship in the form of an inequality was generated relating the geometric parameters of the VG with the diffusion characterisitics of the passage:

$$\begin{aligned}
\frac{F(AR, d/C)G(\alpha, h/\delta)}{H(DF)} &\leq 1 \\
F(AR, d/C) &= \left(\frac{AR + k_2}{k_1}\right)\left(\frac{d}{C}\right) \\
G(\alpha, h/\delta) &= \left(\frac{1}{\alpha}\right)\left(\frac{1}{\tanh(k_3(h/\delta))}\right) \\
H(DF) &= -\frac{4}{\pi^2}\ln\frac{(1-DF)}{DF}
\end{aligned}$$

where

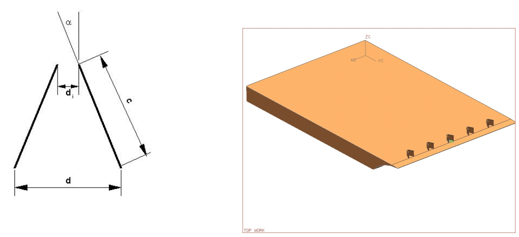
$$k_1 = 1.61; k_2 = 0.48; k_3 = 1.41; k_4 = 1.00; AR = \frac{8}{\pi}\frac{h}{c}; DF = 1 - \frac{V_2}{V_1}$$

where C is the surface arc length; c is the VG chord length; AR is the VG aspect ratio; h is the VG height; δ is the boundary layer height at the VG leading edge; d is the distance between VG trailing edges (see Figure 4); V_1 is the passage throat velocity; V_2 is the passage exit velocity; and DF is a simplified diffusion factor as defined above.

The function H is dependent only upon flow field kinematics (the diffusion factor). Both functions F and G are dependent on geometric characteristics along with the boundary layer thickness. A family of characteristic curves of FG/H were produced by fixing the function G through a choice of α and h/δ and the diffusion factor of 0.7 for the passage under consideration. Two geometric constraints were applied due to physical limitations of using these VG's. The first was due to the constraint of generating two counter-rotating vortices a distance d apart using VG's at an angle of attack α. Figure 4 shows a top-down view of the VG's with relevant dimensions. The second geometric constraint was derived from a heuristic argument that the distance, d, between the vortex pair should be less than the height of the VG. This is applied so that the vortex image does not dominate initially and cause the vortex pair to migrate apart. A geometric configuration was chosen that maximizes the circulation and yet is acceptable according to the two geometric constraints. The boundary layer thickness for the wind tunnel at the throat was approximated from a CFD calculation at 0.254 mm. Using the surface arc length of the passage, C, of 31 mm gives the following VG geometric parameters:

$$h = 3.81mm; d = 3.765mm; c = 3.962mm; \alpha = 25^o, d_i = 0.3765mm$$

Figure 4 shows the flow control module upper plate obtained by using these geometric parameters at a spacing of $4.5d$ between VG pairs. The spacing between pairs of vortices was chosen based on guidelines outlined in 5.



(a) Counter-rotating VG Geometry Definition

(b) VG Flow Control Upper Plate

Figure 4: VG geometry and FCAD plate

Future Direction

The embedded streamwise vorticity experiment will be tested and stereo PIV measurements take in order to analyze the streamwise vortex generation and migration. Also, exit total pressure measurement traverses will be added to the experimental data collection. Methods to address endwall effects will also be considered and modeling performed to enhance the data obtained from experimental measurements.

Acknowledgement

This work was sponsored (in part) by the Air Force Office of Scientific Research, USAF. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Office of Scientific Research or the U.S. Government.

References

[1] Merchant, A., Kerrebrock, J. L., Adamczyk, J. J., and Braunscheidel, E., "Experimental Investigation of a High Pressure Ratio Aspirated Fan stage," *ASME Journal of Turbomachinery*, Vol. 127, January 2005, pp. 43–51.

[2] Luedke, J., Graziosi, P., Kirtley, K., and Cerretelli, C., "Characterization of Steady Blowing for Flow Control in a Hump Diffuser," *22nd Applied Aerodynamics Conference and Exhibit*, Providence, RI, 2004, AIAA Paper no. 2004-4963.

[3] Kirtley, K. R., Graziosi, P., Wood, P., Beacher, B., and Shin, H. W., "Design and Test of an Ultra-Low Solidity Flow-Controlled Stator," *ASME Turbo Expo 2004*, Vienna, AU, 2004, ASME Paper no. GT2004-53012.

[4] Carter, C. J., Guillot, S. A., Ng, W. F., and Copenhaver, W. W., "Aerodynamic Performance of a High-Turning Compressor Stator with Flow Control," *37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Salt Lake City, UT, 2001, AIAA Paper no. 2001-3973.

[5] Pearcey, H. H., "Shock Induced Separation and Its Prevention by Design and Boundary Layer Control," *Boundary Layer and Flow Control*, edited by G. V. Lachmann, Vol. 2, Pergamon Press Inc., New York, 1961, pp. 1170–1349.

[6] Kuethe, A. M. and Chow, C.-Y., *Foundations of Aerodynamics: Bases of Aerodynamic Design*, John Wiley & Sons, 4th ed., 1986.

[7] Wendt, B. J., "Parametric Study of Vortices Shed from Airfoil Vortex Generators," *AIAA Journal*, Vol. 42, No. 11, 2004, pp. 2185–2195.

Personnel Supported

Dr. Jordi Estevadeordal	Research Scientist, Innovative Scientific Solutions Inc. (100%)
Dr. S. Todd Bailie	Research Scientist, NRC Post Doctorate Program (33%)
Mr. David Car	Research Scientist (10%)
Dr. Steven L. Puterbaugh	Research Scientist (10%)

Publications

Gorrell, S. E., Car, D., Puterbaugh, S. L., Estevadeordal, J., and Okiishi, T. H., "An Investigation of Wake-Shock Interactions in a Transonic Compressor with DPIV and Time-Accurate CFD," ASME Paper GT2005-69107, June, 2005.

McCray, T.W., Estevadeordal, J., and Puterbaugh, S.L., "Parallel Computing for Linux Clusters: Application to Particle Image Velocimetry," 43^{rd} AIAA Aerospace Sciences Meeting, Reno, NV, January, 2005.

Estevadeordal, J., Goss, L., Car, D., and Bailie, S.T., "PIV with LED: Particle Shadow Velocimetry," 43^{rd} AIAA Aerospace Sciences Meeting, Reno, NV, January, 2005.

Honors and Awards Received

None.

Transitions

None.